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Bidirectional Static Load Test (BDSLT) on a Versatile Barrette Foundation for High-Rise Building in Dubai

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Abstract. Barrettes are common foundations for high-rise buildings, especially because of their high bearing capacity, vertical as well as lateral loads. Recently barrettes have been demonstrated to be more useful for small plots receiving highly concentrated building loads with limited space between foundations. The idea of a single barrette that can replace a group of conventional piles results in a more stable, economical, and reliable foundation system. Bi-Directional Static Load Test (BDSLT), modern full-scale proofing load test method, carried out using a hydraulically driven, purpose-built, calibrated, sacrificial loading jacks installed within the foundation unit. This paper articulates the results of three barrette tests of 2.80mx1.20m size from a 300m high-rise La Maison Residential Tower, Dubai, UAE. The main objective of this load test was to proof-load the test barrettes over 160000KN. For this purpose, 9x900 tons of capacity hydraulic jacks and eight levels of vibrating wire-type strain gauges comprising four units at each level were utilized. The settlement results of a 47m deep barrette indicate a total settlement of 6.5 mm at the working load of 54,000 KN that is in good agreement with the 6.20 mm induced from the bi-directional static load tests. The interpretation of the load test results pooled with finite-element analyses aided optimization of the barrette capacities maintaining a sufficient factor of safety. The barrette total capacity was evaluated based on the load test results and interpretation of deformation, load distribution, induced unit skin friction, and up to 11% reduction of the current length was proposed.

Keywords: Barrette, Bidirectional, Load, Dubai

1 Introduction

Barrettes are large rectangular piles that are constructed either by the use of a device with rotating cutter heads. The excavation for a barrette is performed under bentonite or a polymer that keeps the hole open as for a conventionally drilled pile. Once the barrette is excavated and the bentonite de-sanded, a steel cage is lowered into the hole, and then concrete is trimmed into the base of the hole, displacing the bentonite. Barrettes can be constructed in L, T, H, or cruciform shapes in the plan if so desired by cutting the rectangular hole several times to form the shape. Barrette foundations have been used for many years and are treated as rectangular piles in foundation engineering applications. In the Middle East, a fast-growing construction hub, excavated rectangular barrettes, and large diameter bored piles are commonly adopted as the foundation units in high rise buildings and infrastructure projects [1**]**. The founding strata for these units are usually medium to hard rocks, relying on shaft resistance, are designed. Nevertheless, pile design parameters must be geotechnically and structurally verified by using preliminary pile loading tests before they are used in the final design. Deprived of performing such load tests on-site, unit shaft resistance and settlement cannot be identified and not normally permitted by the local authorities. In the last two decades, many full-scale compression loading tests on instrumented barrettes and bored piles have been performed using BDSLT in the United Arab Emirates (UAE) to verify the design parameters. The bidirectional static load test (BDSLT) has been around since the early 1970s. The first commercial development came about in the early 1980s in Brazil and about a decade later in the USA [2-4]. Due to the many advantages over the conventional top-down load test, the Bidirectional Static Loading Test (BDSLT) using the hydraulically driven jacks is becoming an increasingly popular way to determine the ultimate capacity of deep foundations. The high capacity sacrificial jack is installed within the foundation unit at the chosen location, where it is typically halfway down the pile capacity length of the foundation [5].

This method is internationally accepted and referred to in the international standards [6-8]. BDSLT has been employed on several barrette projects in the Middle East and other Asian countries and has been developed into an efficient and cost-effective method. With an increase in demand for the foundations unites that utilize barrette construction for their foundation design in the UAE, it is evident that BDSLT will play a vital role in future barrette foundation developments. This article discusses the application of BDSLT on an instrumented versatile deep barrette foundation to identify the settlement, load distribution, and unit skin friction, and thereby to verify the foundation design for value engineering at La Maison Residential high rise building, Dubai, UAE.

2 Geological Conditions

The geology of the United Arab Emirates, and the Arabian Gulf area, has been substantially influenced by the deposition of marine sediments associated with numerous sea level changes during relatively recent geological time. With the exception of mountainous regions shared with Oman in the north- east, the country is relatively low-lying, with near surface geology dominated by Quaternary to late Pleistocene age, mobile aeolian dune sands, and sabkha/evaporites deposits. The geologically stable Arabian Plate is separated from the unstable Iranian Fold Belt by the Arabian Gulf. It is believed that a tilting of the entire Arabian Plate occurred during the early Permian period, resulting in uplift in southern Yemen, and depression to the north- east. Crustal deformations and igneous intrusions occurred in the north- east as a result of this movement. Subsequent tectonic movements, peripheral to the folding of the Iranian Zagros Range, during the Plio-Pleistocene epoch, probably contributed to the formation of both the Arabian Gulf depression, and the mountainous regions shared by the United Arab Emirates and Oman in the north- east. The near surface geology of the Dubai region is dominated by Aeolian dune sand deposits of Holocene to Pleistocene age. These deposits typically comprise fine grained silty calcareous sand, which is commonly dense and variably cemented beneath a shallow, loose, normally consolidated mobile layer. Although variable, the degree of cementation generally increases with depth, such that the variably cemented sand grades to predominantly calcareous sandstone. Very silty, gypsiferous sabkha and evaporate layers occur occasionally within the Aeolian sand deposits [9]. Although surficial sabkha deposits are found throughout the coastal belt of the Arabian Gulf, and far inland in the western and southern parts of the United Arab Emirates, they are not particularly common in the Dubai region. These superficial deposits were underlain by alternating beds of siliceous calcarenite, calcareous sandstone, siltstone, and conglomerates [10].

The Barrette test location is positioned in Dubai Business Bay, about 2.0 km southeast from Burj Khalifa. The site is of rectangular shape featuring an approximate area of 90m by 60m. Tower footprint is covering a 30m by 50m area. The local geology is characterized by the presence of the Barzaman Formation which is encountered at depths greater than 23m. The Barzaman formations include reddish-brown conglomerates, brecciated dolomitic calcisitites, and breccias with clasts of coarse gravel and cobble size of limestone [10]. The cementing material in the calcisiltic breccias is relatively weaker, a greenish-grey colour and is probably the clay mineral palygorskite. The Barzaman formation is overlain by the reddish-brown sandstones, which are extremely weak to weak with localized medium beds of calcilutite breccia. The sandstones are fine to medium sand size with a cementing material that imparts a very inconsistent strength to the rock. The reddish-brown sandstones are overlain by a brown to light brown Calcarenite (Ghayathi Formation). The Calcarenite are locally thinly laminated, fine to medium-grained. Localized medium beds of imperfectly laminated or massive Calcarenite with fine to medium clasts are also encountered [5]. The general geotechnical parameter used for the foundation design is provided in Table 1.

Table 1. The general geotechnical parameters

Strata	Depth (mDMD)	SPT N	Allowable Unit Skin Friction (KPa)
Medium dense silty fine sand with some cemented pieces	0.00 to -18.00	20-50	-
Calcarenite/ Calcareous Sandstone, slightly to moderately weathered interbedded with	-18.00 to -27.50	-	100-250

cemented calcareous sand			
Weak to moderately weak brown Conglomerate, slightly to moderately weathered	-27.50 to -33.00	-	170-210
Calcisiltite/Calcareous Siltstone moderately weathered interbedded with cemented calcareous silt	-33.00 to -40.00	-	100- 140
Weak to moderately weak light brown Calcareous Siltstone interbedded with cemented calcareous silt	-40.00 to -45.00		100- 130
Weak to moderately weak light brown Calcisiltite interbedded with cemented calcareous silt	-45.00 to -70.00		100-150

3 Methodology

Barrette excavation was carried out under the piling contractor's work plan as approved by the Engineer/Contractor. Upon reaching the final toe elevation, the pile bottom was cleaned and approved by the Engineer/Contractor for concrete placement. The hydraulic cell assembly, related hydraulic supply, and instrumentation were lowered into the pile attached to the steel cage. The steel cage was fabricated in several pieces and spliced together over the bored hole. The number of cages was kept to a minimum to speed up the installation process. The first section of the reinforcing cage containing the hydraulic cell assembly was lowered into the borehole. The second cage section was then lowered vertically into position and spliced to the top of the first cage (Fig 1). After the entire reinforcing cage was lowered into the shaft, without any steel casing as the working platform level was about 1.0 to 1.50m above the cutoff level during concrete placement. Concrete placement commences utilizing a suitable size tremie pipe of sufficient length to extend beyond the hydraulic cell assembly to the toe of the pile. Cutouts of sufficient sizes were provided in the hydraulic cell steel bearing plates to accommodate the tremie pipe. A funnel was also constructed between the opening in the top plate of the hydraulic cell assembly and the main vertical rebar to guide the concrete tremie pipe through the steel bearing plates. The funnel also serves as a means of preventing the tremie pipe from accidentally hitting the hydraulic fittings on the cell top by forming a physical barrier apart from serving as a guide. Further protection for the hydraulic hoses was in the form of foam shields and protection bars leading from the hydraulic fittings to the cell top the cage vertical rebar which protects the hoses from the effects of flowing concrete. The concrete was placed up to the designed cut-off level as per the concreting procedures. Reinforcing steel or steel angle iron was welded between the top and bottom bearing plates before the lifting process. These temporary supports were cut out when the cage was lowered into the hole. Tell-tale tubes were installed to measure the cell top and bottom movements. The hydraulic cell is attached to the reinforcement steel cage to ensure its location and depth are located precisely. The size of the barrette was 2.80mx1.20m and one 350mm diameter tremie pipe was used for the inflow of class C75/20 (OPC+36%GGBS+6%MS) concrete.

Fig.1. Barrette installation

After the concrete reaches a minimum required strength, the test may be started (Fig.2). As the load is applied to the hydraulic cell, it begins working in two directions: upward against upper skin friction and downward against lower skin friction and base resistance. BDSLT is considered to be complete after reaching the ultimate capacity above or below the hydraulic cell or upon reaching the maximum capacity of the hydraulic cells. Instrumentation includes hydraulic cell expansion using tell-tale rods and displacement transducers; pile movement using displacement transducers; skin friction, strain, and load transfer at different levels using vibrating wire concrete embedded strain gauges. The load increments were applied as specified in the loading schedule and each successive load increment was held constant by adjusting the hydraulic jack pressure until the settlement criteria were met. Data acquisition of all embedded instruments was connected to a data logger to a laptop computer allowing the data to be recorded and stored automatically at stipulated intervals and displayed in real-time.

Fig. 2. Barrette load test set up

A total of three bi-directional static load tests were carried out at the proposed La Maison Residential Tower on Plot no. BB-B04-001 at Business Bay, Dubai. Tests were carried out from 27th December 2016 to the 6th of January 2017. The barrette size was 2.80 x 1.20 m with a maximum length of 48.60m below the finished level. All barrettes were tested to a maximum load of more than three (3) times the expected working load to verify their capacity (Table 2). Tests were performed in sacrificial barrettes using a hydraulic jack assembly comprising of nine 900 tonne capacity bi-directional jacks, each jack can achieve an additional capacity of 15-20% during over jacking. Eight levels of vibrating wire-type strain gauges comprising four units at each level were also installed on the test pile to measure strains at nominated locations. The data obtained from the site was analysed using an equivalent top-loading method to identify the elastic settlement [11, 5]

4 Results and Discussion

The data obtained from all the three tests were analyzed and results are presented. Table 2 gives the details of barrettes with hydraulic jack position and strain gauge levels. Table 3 summarizes Load and settlement obtained for the three barrette load tests performed.

Table 2. Instrumentation details of Test barrettes

Test Barrette details	GB1	GB2	GB3	Rock Profile
Diameter (mm)	2.80x1.20	2.80x1.20	2.80x1.20	Calcarenite/Calcareous Sandstone (-1800 to -27.50)
Length(m)	45.125	47.825	48.60	
Cutoff level (mDMD)	-24.875	-22.175	-20.375	
Toe level (mDMD)	-70.00	-70.00	-68.975	
Jack position (mDMD)	-48.30	-46.90	-45.40	Conglomerate (-27.50 to -33.00)
Working load (kN)	54000	54000	54000	
Test load (KN)	162000	162000	162000	
Maximum achieved load (kN)	180320	183110	183120	Calcisiltite/Calcareous Siltstone (-33.00 to -40.00)
Strain Gauge levels (mDMD)	-27.0, -33.10, -39.2, -45.3, -51.3, -57.2, -63.1, and -69.0	-24.3, -30.8, -37.3, -43.9, -49.9, -56.2, -62.5, and -69.0	-22.5, -29.1, -35.7, -42.4, -48.4, -54.9, -61.4, and -67.9	Calcareous Siltstone (-40.00 to -45.00)
				Calcisiltite (-45.00 to -70.00)

Table 3. Settlement Summary of Bidirectional Static Load Tests

Barrette no.	Working load (KN)	Test load (KN)	Achieved load (KN)
	54000	162000	180320
GB1		Elastic settlement (mm)	
	6.40	19.20	24.40
	54000	162000	183110
GB2		Elastic settlement (mm)	
	6.20	20.80	25.60
	54000	162000	183120
GB3		Elastic settlement (mm)	
	6.10	20.30	25.70

4.1.FEM Modelling

Generally, a geotechnical analysis counts to ensure that the subsoil can stand the load transmitted by the supporting system to ensure a proper foundation design. Soil-structure interaction phenomena were found to have a significant impact on the design. The analysis is required for foundation elements when soil- structure interaction and multistage loading types are considered. The axial capacities of barrettes can be parametrically verified for different soil materials. The three-dimensional finite element program, MIDAS GTS-NX was chosen to analyze the barrette capacity using settlement and unit skin friction parameters obtained from the load tests. Finite element analyses were carried out to support the structural design, and to obtain settlement and capacity estimates. Results on a 47m barrette, when applying the revised soil parameters, indicated a total vertical settlement of 6.5mm under the working load of 54,000 kN and a total settlement of 15.70mm at 200% of the working loads which compares well with the load settlement curve as developed from load tests (Table 4). It should be noted that induced settlement at the working load is well within the acceptable limit of 1.5% of the equivalent diameter as specified from BS 8004, 2015 Code of Practice for Foundations, Section 6.8.2.1 [12].

Table 4. Settlement analysis of a single barrette element

Method	Barrette Dimensions (m x m)	Length (m)	Total Vertical Settlement (mm) 100% Working Load	150% Working Load	200% Working Load
Load Test	2.80x1.20	47	6.20	9.70	13.90
FEM	2.80x1.20	47	6.50	11.10	15.70

The above results show that the results of the load test are in good agreement with the design values. The results of the single barrette model will be further utilized to modify the ground parameters to match the actual results in the Barrette group modeling in further stages of the group analysis to estimate total settlement under the group behavior. The three barrette tests showed similar results with settlement ranging from 6.10 mm to 6.40 mm at the working load of 54,000 kN and up to 19.20 to 20.80mm at three times the working load. Settlement results of a 47m deep 2.80 x 1.20 m barrette indicate a total settlement of 6.5 mm at the working load of 54,000 KN that is in good agreement with the 6.20 mm induced from the bi-directional static load tests.

4.2.Barrette Capacity

Based on the available results from barrette load tests, the ultimate skin friction provided [13] was revisited to match the results of 100% loading conditions. Mobilized skin friction for the three tests at 100%, 200%, and 300% of the working load (Table

5) and theoretical values are presented (using the highest cutoff level barrette no.GB3, -20.375 m DMD) in figure 3. Based on the analysis, modified capacity for a 2.80 x 1.20 m barrette with depth are obtained (Fig.4). A comparison between the revised (from barrette load test results) and preliminary barrette capacity in compression is presented in figure 5. The test results show a good agreement with the theoretical and design parameters.

Table 5. Mobilized Unit Skin friction from BDSLT

Strain Gauge Levels (from top to bottom)	GB1			GB2			GB3		
	Unit skin friction (KPa)								
	100% Load	200% Load	300% Load	100% Load	200% Load	300% Load	100% Load	200% Load	300% Load
1 to 2	64	106	195	70	134	151	38	161	253
2 to 3	162	275	361	117	263	438	128	239	400
3 to 4	179	417	655	182	352	540	185	340	494
4 to Jack	283	573	812	299	553	826	325	564	737
5 to Jack	325	603	896	405	649	896	317	559	727
5 to 6	192	425	590	201	421	636	222	353	464
6 to 7	172	298	441	83	211	363	116	276	404
7 to 8	42	109	211	40	90	122	20	119	287

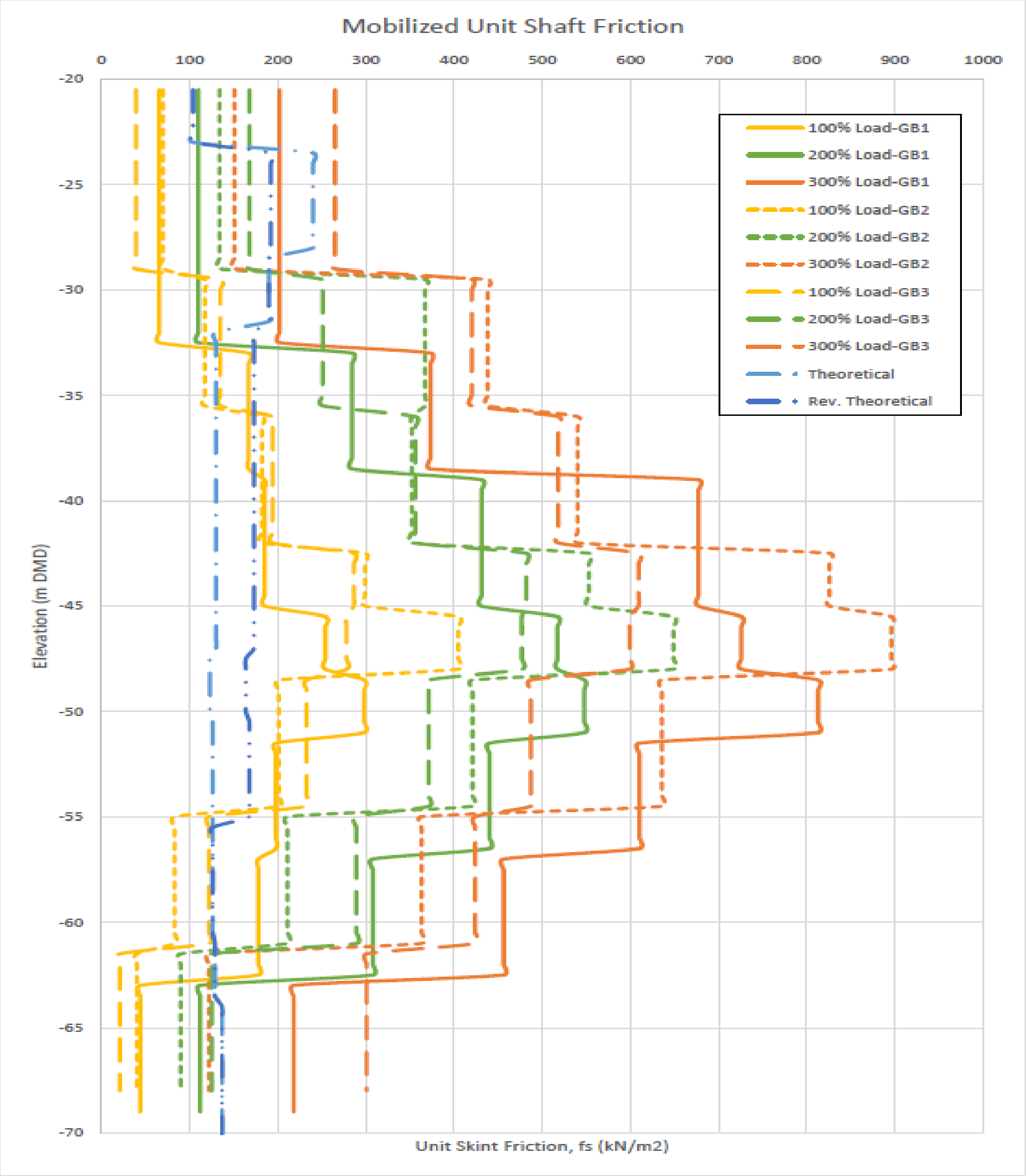


Fig.3. Mobilized skin friction vs load

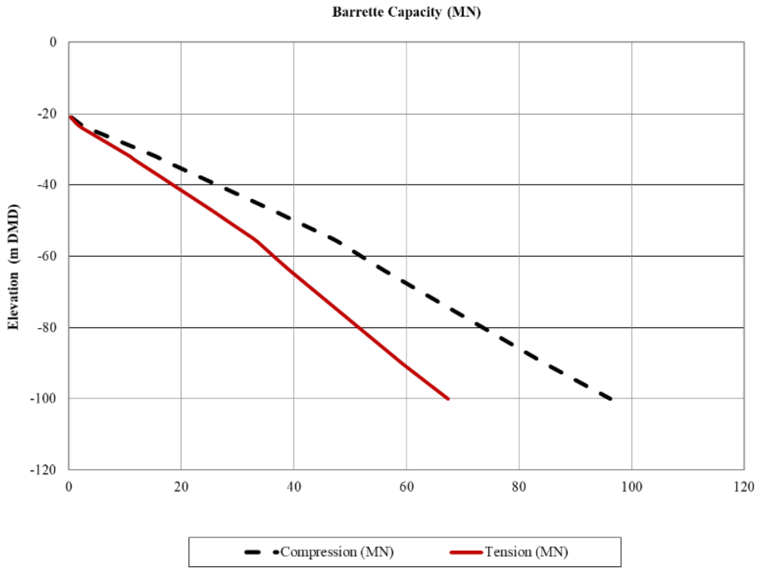
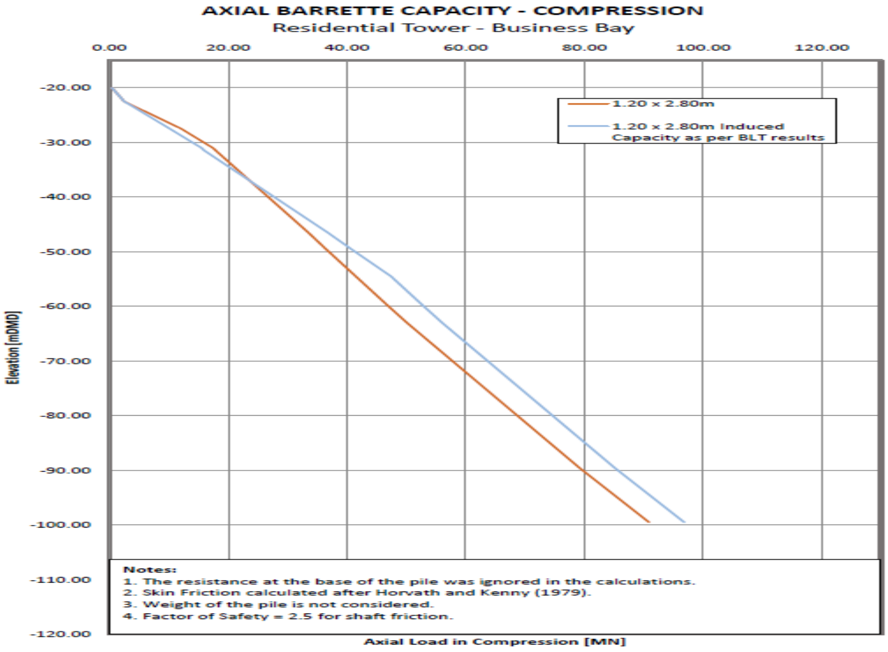


Fig.4. Revised barrette capacity based on BDSLT results



Notes:
1. The resistance at the base of the pile was ignored in the calculations.
2. Skin Friction calculated after Horvath and Kenny (1979).
3. Weight of the pile is not considered.
4. Factor of Safety = 2.5 for shaft friction.

Fig.5. A comparison between load test and preliminary barrette capacity

Table 6. Designed Barrette after BDSLT

Structural element		Cutoff level (mDMD)	Toe level (mDMD)	Compression load (KN)
Barrette	2.80mx1.20m	-23.00	-65.00	54000

In order to monitor foundation behavior, strain gages were installed in eight levels of barrettes to compare the calculated and actual behavior of the foundation. Preliminary load tests, performed on three barrettes, were established in order to achieve skin friction up to 3.0 times larger than the estimated serviceability values. During the assessment of the load test results, we considered that design skin friction may be increased from values reported before pile testing and the revised recommended values of allowable shaft friction are required. The side resistances determined from the load tests are higher than the initial design values adopted, leading to possible optimizations. The initial theoretical allowable unit skin friction was used for the preliminary barrette design (Fig. 3). Based on the three load test results, the maximum mobilized skin friction value calculated from the strain gauge readings is in the range of around 253 to 896KPa. The unit skin friction values are increasing linearly and do not show evidence of developing geotechnical failure. For all of the barrettes, the unit shaft resistance was mobilized at an average value of settlement equal to about 20 mm. This indicates that the barrettes can be still loaded to mobilize ultimate skin friction resistance along the complete shaft length. It can be concluded that the load tests can appropriately represent the characteristics of soil strata and the side resistances determined are much larger than the design values adopted. Hence, based on the theoretical load test results, revised theoretical values were derived and these values were used for the execution of barrettes in the site. Based on the above result, for a permanent compression load of 54,000 kN (Table 6) for the barrettes and assuming a cut-off level at -23.00m DMD, a barrette length of 42m is found to be sufficient for the foundation design. This corresponds to a total length reduction of 11% after the interpretation of barrette load test results.

5 Conclusions

Load test results and analysis indicate that the barrette capacities can be further optimized maintaining a sufficient factor of safety. The outcomes indicate that the barrette design can be optimized in length up to 11%, reducing the current barrette length from 47m to 42m deep. Preliminary settlement results of a 47m deep 2.80 x 1.20 m size barrette indicate a total settlement of 6.5 mm at the working load of 54,000 kN that is in good agreement with the 6.20 mm induced from the bi-directional static load tests. It is identified that test barrettes can be used for foundation testing to virtually any high loads. The results obtained from the testing has to lead to a reassessment of the original pile design to benefit future stakeholders in designing economically viable high rise building projects. BDSLT enables full-scale testing of the foundation element proposed for the working foundations, allowing the designer to quantify the geotechnical parameters precisely. Moreover, the large dimension of the barrette often permits a variety of loading arrangements to virtually any high loads that are not constrained by the physical dimensions of the foundation element as would be the case in a piled foundation.

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